ζ Oph and the weak-wind problem

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ABSTRACT
Mass-loss rate, $\dot{M}$, is one of the key parameters affecting evolution and observational manifestations of massive stars, and their impact on the ambient medium. Despite its importance, there is a factor of ~ 100 discrepancy between empirical and theoretical $\dot{M}$ of late-type O dwarfs, the so-called *weak-wind problem*. In this Letter, we propose a simple novel method to constrain $\dot{M}$ of runaway massive stars through observation of their bow shocks and Strömgren spheres, which might be of decisive importance for resolving the weak-wind problem. Using this method, we found that $\dot{M}$ of the well-known runaway O9.5 V star ζ Oph is more than an order of magnitude higher than that derived from ultraviolet (UV) line-fitting (Marcolino et al. 2009) and is by a factor of 6 to 7 lower than those based on the theoretical recipe by Vink et al. (2000) and the Hα line (Mokiem et al. 2005). The discrepancy between $\dot{M}$ derived by our method and that based on UV lines would be even more severe if the stellar wind is clumpy. At the same time, our estimate of $\dot{M}$ agrees with that predicted by the moving reversing layer theory by Lucy (2010).

Key words: H II regions – circumstellar matter – stars: mass-loss – stars: winds, outflows – stars: individual: ζ Oph.

1 INTRODUCTION

Mass-loss rate, $\dot{M}$, is one of the key parameters defining the evolutionary sequence of massive stars and the end products of their evolution (e.g. Chiosi & Maeder 1986; Langer et al. 1994). Although there is good agreement between the theoretically predicted $\dot{M}$ of early-type O stars, i.e. stars more luminous than $\approx 10^{5.2} L_\odot$, and those derived empirically, there is a factor of 100 discrepancy between the theoretical and empirical $\dot{M}$ of late-type O dwarfs (e.g. Martins et al. 2005b, 2012; Marcolino et al. 2009), the so-called *weak-wind problem* (see Hillier 2008 and Puls, Vink & Najarro 2008 for reviews).

$\dot{M}$ is also one of the main parameters defining the impact of massive stars on the interstellar medium (ISM) through the formation of stellar wind bubbles (e.g. Avedisova 1972; Castor, McCray & Weaver 1975) and bow shocks (Baranov, Krasnobaev & Kulikovskii 1971; Weaver et al. 1977). The characteristic scale of these structures (typically tens of pc for bubbles and tenths of pc for bow shocks) is proportional to $\dot{M}$ and therefore, in principle, can be used to constrain this important parameter. The use of the wind

bubbles for this goal, however, is hampered because most massive stars reside in parent clusters so that their bubbles are the result of the joint action of all massive stars in the cluster, which precludes us from constraining the wind parameters of individual stars. On the other hand, wind bubbles created by massive stars ejected into the field (the runaway stars) rapidly turn into bow shocks (Weaver et al. 1977), whose sizes depend on individual characteristics of their underlying stars. This makes bow shocks an important tool for constraining $\dot{M}$ of massive stars (Gull & Sofia 1979; Kobulnicky, Gilbert & Kiminki 2010) and thereby for resolving the weak-wind problem.

The characteristic size of a bow shock depends on the stellar wind momentum rate (the product of $\dot{M}$ and the terminal velocity of the stellar wind, v_∞), the space velocity of the star, and the number density of the ISM, n. The space velocities of nearby stars can be accurately determined by measuring their proper motions, parallaxes and radial velocities. Then $\dot{M}v_\infty$ can be derived if n is known.

In this Letter, we propose a simple novel method to constrain $\dot{M}$ of massive stars based on detection of well-defined H II regions around bow-shock-producing runaways. Detection of these structures around field O stars allows us to express $\dot{M}v_\infty$ through observables (bow shock stand-off distance, Strömgren radius and space velocity) and the total

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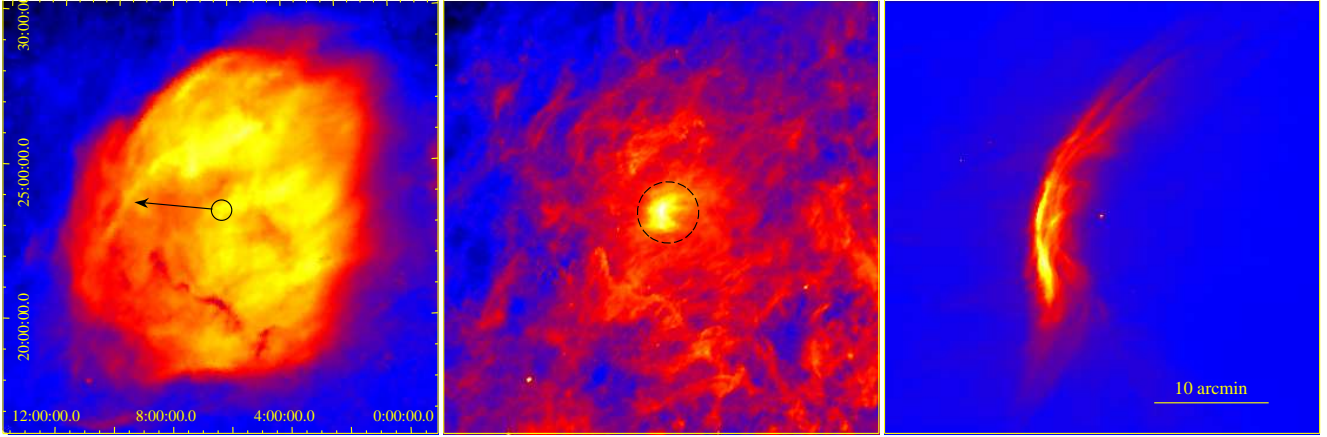
Figure 1. *Left*: SHASSA Hα image of the H II region Sh 2-27. The position of the ionizing star, ζ Oph, is marked by a circle, while the direction of its peculiar (transverse) velocity is indicated by an arrow. The image is oriented with Galactic longitude (in units of degrees) increasing to the left and Galactic latitude increasing upward. *Middle*: *IRAS* 60 μm image of the same field with the bow shock generated by ζ Oph indicated by a dashed circle. The images were generated by the NASA's SkyView facility (McGlynn, Scollick & White 1998). *Right*: *Spitzer* 24 μm image of the bow shock around ζ Oph. The orientation of the images is the same. At a distance of 112 pc, 1 degree corresponds to ≈ 1.93 pc and 10 arcmin to ≈ 0.32 pc.

Table 1. Summary of astrometric and kinematic data on ζ Oph (see text for details).

d (pc)	$\mu_\alpha \cos\delta$ (mas yr^{-1})	μ_δ (mas yr^{-1})	$v_{\rm r,hel}$ (km s^{-1})	$v_{\rm l}$ (km s^{-1})	$v_{\rm b}$ (km s^{-1})	$v_{\rm r}$ (km s^{-1})	v_* (km s^{-1})
112^{+3}_{-2}	15.26 ± 0.26	24.79 ± 0.22	-15.0	26.4 ± 0.1	3.1 ± 0.1	-1.1	26.5 ± 0.1

ionizing-photon luminosity, $S(0)$, which is a well-established quantity for stars of known spectral type and luminosity class. We applied this method to the well-known runaway O star ζ Oph, which according to Marcolino et al. (2009) belongs to the group of weak-wind stars (see Section 2 for a summary of relevant data on this star). The excellent consensus in the literature on v_∞ of ζ Oph allowed us to estimate $\dot{M}$ of this star separately, which turns out to be intermediate between those based on Hα and ultraviolet (UV) lines (Section 3). The discussion of this result and outlook are given in Section 4.

2   ζ OPH, ITS BOW SHOCK AND H II REGION

ζ Oph (HD 149757, HIP 81377) is a nearby ($\approx 112^{+3}_{-2}$ pc; van Leeuwen 2007), single (Garmany, Conti & Massey 1980), rapidly-rotating ($v \sin i \approx 400$ km s^{-1}; Howarth & Smith 2001), runaway (Blaauw 1961), O9.5 Vnn (Morgan, Code & Whitford 1955; Lesh 1968) star with an impressive bow shock (Gull & Sofia 1979; van Buren & McCray 1988) immersed in the H II region Sh 2-27 (Sharpless 1959).

In the left panel of Fig. 1 we present the Hα image of Sh 2-27 originating from the Southern Hemispheric Hα Sky Survey Atlas (SHASSA; Gaustad et al. 2001), which shows an almost circular ($\approx 10°$ or 9.6 pc in diameter) H II region. The middle panel of Fig. 1 shows the *Infrared Astronomical Satellite* (*IRAS*) 60 μm image of the same field with an arcuate structure in the centre of the H II region, which is the bow shock generated by ζ Oph (van Buren & McCray

1988). Using the archival *Spitzer Space Telescope* 24 μm image (Program Id.: 30088, PI: A. Noriega-Crespo) of the bow shock (see the right panel of Fig. 1), we estimated the angular separation between the apex of the bow shock and the star of ≈ 5 arcmin, which corresponds to ≈ 0.16 pc.

In Table 1 we give the parallactic distance, d, and the proper motion components, $\mu_\alpha \cos\delta$ and μ_δ, of ζ Oph (all from the new reduction of the *Hipparcos* data by van Leeuwen 2007), and the heliocentric radial velocity, $v_{\rm r,hel}$, of this star (Wielen et al. 1999). To these data we added the components of the peculiar transverse velocity (in Galactic coordinates), $v_{\rm l}$ and $v_{\rm b}$, the peculiar radial velocity, $v_{\rm r}$, and the total space velocity, $v_* \equiv (v_l^2 + v_b^2 + v_r^2)^{1/2}$, of the star. To calculate v_*, we used the Galactic constants $R_0 = 8.0$ kpc and $\Theta_0 = 240$ km s^{-1} (Reid et al. 2009) and the solar peculiar motion $(U_\odot, V_\odot, W_\odot) = (11.1, 12.2, 7.3)$ km s^{-1} (Schönrich, Binney & Dehnen 2010). For the error calculation, only the errors of the proper motion measurement were considered. It follows from Table 1 that ζ Oph is moving almost in the plane of sky.

The fundamental parameters of ζ Oph were studied in numerous publications, of which the most recent are those by Mokiem et al. (2005) and Marcolino et al. (2009). There is excellent consensus on v_∞ of the star: 1470 km s^{-1} (Prinja, Barlow & Howarth 1990), 1550 km s^{-1} (Repolust, Puls & Herrero 2004) and 1500 km s^{-1} (Marcolino et al. 2009). In what follows, we adopt $v_\infty = 1500$ km s^{-1}. Estimates of $\dot{M}$, however, are very different. The theoretical recipe by Vink, de Koter & Lamers (2000) predicts $\dot{M}_{\rm Vink} \approx$

1.29×10^{-7} M$_\odot$ yr^{-1} (for stellar parameters derived by Marcolino et al. 2009), which is comparable to $\dot{M}_{\mathrm{H}\alpha} \approx 1.43 \times 10^{-7}$ M$_\odot$ yr^{-1}, inferred by Mokiem et al. (2005) from synthesizing the Hα line using the FASTWIND code. A value two orders of magnitude lower, $\dot{M}_{\mathrm{UV}} \approx 1.58 \times 10^{-9}$ M$_\odot$ yr^{-1}, was inferred by Marcolino et al. (2009) from CMFGEN model fits to the UV doublet of C IV $\lambda\lambda$1548, 1551, while Lucy (2010) predicted $\dot{M}_{\mathrm{Lucy}} \approx 1.30 \times 10^{-8}$ M$_\odot$ yr^{-1} by using the updated moving reversing layer theory of Lucy & Solomon (1970).

The fast rotation of ζ Oph makes its spectral classification somewhat ambiguous. Although the widely accepted spectral type is O9.5 V, some other classifications were suggested as well. For instance, Conti & Leep (1974) classified this star as O9 V(e), while Herrero et al. (1992) prefer O9 III. Like Marcolino et al. (2009), we adopt the spectral type of O9.5 V, so that $S(0) = 3.63 \times 10^{47}$ s^{-1} (Martins, Schaerer & Hillier 2005b). The basic parameters of ζ Oph are summarized in Table 2. To this table we added our estimate of the mass-loss rate, $\dot{M}_{\mathrm{obs}}$, based on the observed parameters of the bow shock and the H II region associated with ζ Oph (see next Section).

3 MASS-LOSS RATE OF ζ OPH

The structure of an H II region created by a moving star depends on the stellar velocity relative to the local ISM. For supersonically moving stars the number density within the H II region is comparable to that of the ambient ISM, while the radius of the H II region is of the order of the Strömgren radius (e.g. Tenorio Tagle, Yorke & Bodenheimer 1979), which is given by (e.g. Lequeux 2005)

$$R_{\mathrm{St}} = \left(\frac{3S(0)}{4\pi\alpha_{\mathrm{B}} n^2} \right)^{1/3}, \qquad (1)$$

where α_{B} is the recombination coefficient of hydrogen to all but the ground state ($\approx 2.6 \times 10^{-13}$ cm^{3}s^{-1} for fully ionized gas of temperature of 10^4 K).

The stellar wind of a moving star interacts with the ISM and produces a bow shock ahead of the star. The minimum distance from the star at which the wind pressure is balanced by the ram and the thermal pressures of the ISM, the stand-off distance, is given by (e.g. Baranov et al. 1971)

$$R_0 = \left[\frac{\dot{M} v_\infty}{4\pi n (\mu m_{\mathrm{H}} v_*^2 + 2kT)} \right]^{1/2}, \qquad (2)$$

where $\mu = 1.4$ is the mean molecular weight, m_{H} is the mass of a hydrogen atom, k is the Boltzmann constant, and $T(\approx 10^4$ K$)$ is the temperature of the (ionized) ISM.

Eliminating n between equations (1) and (2), one has the 'observed' stellar wind momentum rate

$$\dot{M}_{\mathrm{obs}} v_\infty = 1.57 \times 10^{25} \text{ g cm s}^{-2} \left(1 + \frac{1}{M^2} \right) \left(\frac{R_0}{0.1 \text{ pc}} \right)^2$$

$$\times \left(\frac{v_*}{10 \text{ km s}^{-1}} \right)^2 \left(\frac{S(0)}{10^{48} \text{ s}^{-1}} \right)^{1/2} \left(\frac{R_{\mathrm{St}}}{10 \text{ pc}} \right)^{-3/2}, \quad (3)$$

where $M = v_*/c_{\mathrm{s}}$ is the isothermal Mach number and $c_{\mathrm{s}} = (2kT/\mu m_{\mathrm{H}})^{1/2}$ is the isothermal sound speed (≈ 10.9 km s^{-1} for $T = 10^4$ K). For $R_0 = 0.16$ pc, $v_* = 26.5$ km s^{-1}, $S(0) =$

3.63×10^{47} s^{-1}, and $R_{\mathrm{St}} = 9.6$ pc, one has from equation (3) that $\dot{M}_{\mathrm{obs}} v_\infty \approx 2.1 \times 10^{26}$ g cm s^{-2}. Thanks to the excellent consensus on v_∞ of ζ Oph (see Section 2), one finds $\dot{M}$ of this star separately, $\dot{M}_{\mathrm{obs}} = 2.2 \times 10^{-8}$ M$_\odot$ yr^{-1}. This is ≈ 14 times larger than $\dot{M}_{\mathrm{UV}}$, 7 times lower than $\dot{M}_{\mathrm{H}\alpha}$, and comparable to $\dot{M}_{\mathrm{Lucy}}$. The discrepancy between $\dot{M}_{\mathrm{UV}}$ and $\dot{M}_{\mathrm{obs}}$ would be even more severe if the wind is clumpy. For instance, $\dot{M}_{\mathrm{UV}}$ should be reduced by a factor of three ($\sim \sqrt{f}$) if the volume filling factor, f, in the wind is ~ 0.1 (Marcolino et al. 2009), so that $\dot{M}_{\mathrm{obs}} \approx 40 \dot{M}_{\mathrm{UV}}$.

Using equations (2) and (3), one finds $n \approx 3.6$ cm^{-3}, which agrees well with estimates of the electron number density within Sh 2-27 of ≈ 3.0 cm^{-3} (based on radio observations, Hα surface brightness, and studies of interstellar absorption lines; Gull & Sofia 1979 and references therein) and the average line of sight electron and neutral hydrogen densities towards ζ Oph of ≈ 4.0 cm^{-3} (Howk & Savage 1999; scaled to d=112 pc).

Note that $\dot{M}_{\mathrm{obs}}$ was derived for $d = 112$ pc, while Marcolino et al. (2009) adopted a somewhat larger distance of 146 pc. An even larger value, $d = 222$ pc, was suggested by Megier et al. (2009), whose estimate is based on the empirical relationship between the strength of the interstellar Ca II lines and the distances to early-type stars. Since v_* scales with the distance as $d^{0.6}$ ($v_* \approx 31.2$ and 41.7 km s^{-1} for $d = 146$ and 222 pc, respectively), one finds that $\dot{M}_{\mathrm{obs}} \propto d^{1.7}$, so that the larger the distance the larger the discrepancy between $\dot{M}_{\mathrm{obs}}$ and $\dot{M}_{\mathrm{UV}}$, namely $\dot{M}_{\mathrm{obs}} \approx 22 - 45 \dot{M}_{\mathrm{UV}}$ for d in the range from 146 to 222 pc. Correspondingly, $\dot{M}_{\mathrm{H}\alpha}$ remains larger than $\dot{M}_{\mathrm{obs}}$ by a factor of ≈ 2 to 4. $\dot{M}_{\mathrm{Vink}}$ also depends on the adopted distance (via the stellar luminosity; Vink et al. 2000); this would decrease (increase) $\dot{M}_{\mathrm{Vink}}$ by a factor of a few for $d = 112$ (222) pc.

Similarly, it follows from equation (3) that $\dot{M}_{\mathrm{obs}} \propto S(0)^{1/2}$, so that $\dot{M}_{\mathrm{obs}} \approx 21 \dot{M}_{\mathrm{UV}}$ (or $\approx 0.2 \dot{M}_{\mathrm{H}\alpha}$) if ζ Oph is an O9 V star (Conti & Leep 1974), and $\dot{M}_{\mathrm{obs}} \approx 37 \dot{M}_{\mathrm{UV}}$ ($\approx 0.4 \dot{M}_{\mathrm{H}\alpha}$) if its spectral type is O9 III (Herrero et al. 1992). Here we used the calibrations of Martins et al. (2005b).

On the other hand, the possible leakage of ionizing photons from the H II region (caused by porosity of the ISM; see Wood et al. 2005 and Section 4) would reduce our estimate of $\dot{M}_{\mathrm{obs}}$. Conservatively assuming that a half of the photons escape from Sh 2-27, one finds that $\dot{M}_{\mathrm{obs}}$ should be reduced by a factor of ≈ 1.4.

Note also that the possible existence of large-scale internal flows in the H II region (e.g. caused by photoevaporation of molecular clumps in the ISM; see Section 4) also can affect the estimate of $\dot{M}_{\mathrm{obs}}$ because R_0 depends on the stellar velocity relative to the local ISM. Assuming that the characteristic velocity of the photoevaporation flows is of order of the sound speed in the ionized gas, i.e. ~ 10 km s^{-1}, one finds that $\dot{M}_{\mathrm{obs}}$ might either be larger or smaller by a factor of up to ≈ 2 if the flow velocity is antiparallel or parallel to the vector of the space velocity of ζ Oph.

Finally, we note that the fast rotation of ζ Oph might make the stellar wind anisotropic by increasing $\dot{M}$ in the equatorial zone (Friend & Abbott 1986). This in turn might affect the geometry of the bow shock and the UV line and Hα diagnostic. The Hα diagnostic would also be unreliable if the Oe status of ζ Oph is due to the presence of a circumstellar disk (see, however, Vink et al. 2009). The anisotropy effects

Table 2. Basic parameters of ζ Oph (see text for details).

Spectral type	v_∞ ($\mathrm{km\,s^{-1}}$)	$S(0)$ ($\mathrm{s^{-1}}$)	$\dot{M}_{\mathrm{Vink}}$ ($\mathrm{M_\odot\,yr^{-1}}$)	$\dot{M}_{\mathrm{H}\alpha}$ ($\mathrm{M_\odot\,yr^{-1}}$)	$\dot{M}_{\mathrm{UV}}$ ($\mathrm{M_\odot\,yr^{-1}}$)	$\dot{M}_{\mathrm{Lucy}}$ ($\mathrm{M_\odot\,yr^{-1}}$)	$\dot{M}_{\mathrm{obs}}$ ($\mathrm{M_\odot\,yr^{-1}}$)
O9.5 Vnn	1500	3.63×10^{47}	1.29×10^{-7}	1.43×10^{-7}	1.58×10^{-9}	1.30×10^{-8}	2.2×10^{-8}

cannot be easily estimated, but are unlikely to change our result significantly.

To summarize, the uncertainties in the distance and the spectral type might lead to the increase of $\dot{M}_{\mathrm{obs}}$ by a factor of ≈ 1.5 to 3, while the leakage of ionizing photons from the H II region and the presence of regular (e.g. photoevaporation) flows within the H II region might reduce $\dot{M}_{\mathrm{obs}}$ by a factor of two. From this it follows that $\dot{M}_{\mathrm{obs}}$ would remain at least an order of magnitude larger than $\dot{M}_{\mathrm{UV}}$ and might be comparable to or somewhat lower than $\dot{M}_{\mathrm{H}\alpha}$.

4   DISCUSSION AND FURTHER WORK

We estimated the mass-loss rate, $\dot{M}_{\mathrm{obs}}$, of the candidate weak-wind star ζ Oph using the observed parameters of its bow shock and H II region. We found that $\dot{M}_{\mathrm{obs}}$ is more than ten times larger than $\dot{M}_{\mathrm{UV}}$ inferred by Marcolino et al. (2009). (Recall that the difference between the two estimates would be even higher if the stellar wind is clumpy.) This finding supports the suggestion by Mokiem et al. (2007) that the use of only UV lines might significantly underestimate $\dot{M}$ of late-type O stars, because X-rays created by shocked wind regions can significantly change the wind ionization and thereby reduce the wind emission in the UV lines (see Martins et al. 2005a and Marcolino et al. 2009 for more details). Moreover, the strengths of diagnostic UV lines could also be reduced (for a given $\dot{M}$) if the wind is porous (clumpy) not only spatially, but also in velocity space (Sundqvist, Puls & Feldmeier 2010; Muijres et al. 2011). On the other hand, although the latter effect does not significantly affect the Hα line, the Hα based estimates of $\dot{M}$ should be considered as upper limits because of the wind clumpiness (Repolust et al. 2004).

The latter conclusion is in line with our finding that $\dot{M}_{\mathrm{obs}}$ is ≈ 7 times lower than $\dot{M}_{\mathrm{H}\alpha}$ (derived by Mokiem et al. 2005 using the FASTWIND code). Note that the discrepancy between the two estimates could also be caused by the fact that the FASTWIND code tends to predict a stronger Hα absorption than the CMFGEN one (Puls et al. 2005; Marcolino et al. 2009), which can affect the Hα based estimates of $\dot{M}$. It is plausible therefore that the actual $\dot{M}$ of ζ Oph is indeed somewhere between $\dot{M}_{\mathrm{UV}}$ and $\dot{M}_{\mathrm{H}\alpha}$, as suggested by the work of Lucy (2010) and as found in this Letter. This inference along with the recent finding by Muijres et al. (2012) that the recipe by Vink et al. (2000) might over-predict $\dot{M}$ for late-type O dwarfs provides an avenue for resolving the weak-wind problem.

Our estimate of $\dot{M}_{\mathrm{obs}}$ was obtained under the assumption that ζ Oph is running through a homogeneous ISM. The [N II]/Hα and [S II]/Hα line ratio maps of Sh 2-27 (based on the Wisconsin Hα Mapper observations; Wood et al. 2005), suggest, however, that the ISM is porous, i.e. contains low-density voids. One might wonder therefore whether ζ Oph is

currently located within such a void so that its $\dot{M}$ is actually $\ll \dot{M}_{\mathrm{obs}}$ and correspondingly comparable to $\dot{M}_{\mathrm{UV}}$.

To address this issue we note that the ionizing radiation of ζ Oph could homogenize the ambient ISM by photoevaporation of density inhomogeneities (e.g. Elmergreen 1976; McKee, van Buren & Lazareff 1984). Thus, our assumption of a homogeneous medium would be correct if the star completely photoevaporates clumps within a region of radius $R_{\mathrm{ph}} \geqslant R_0$ on a time-scale, t_{ph}, shorter than the crossing time of this region, i.e. $t_{\mathrm{ph}} < R_{\mathrm{ph}}/v_*$. The photoevaporation time of a clump of mass M_{cl} located at a distance R_{ph} is given by (McKee at al. 1984)

$$t_{\mathrm{ph}} = 1.7 \times 10^4 \,\mathrm{yr} \left(\frac{n_{\mathrm{m}}}{1\,\mathrm{cm}^{-3}} \right) \left(\frac{S(0)}{10^{48}\,\mathrm{s}^{-1}} \right)^{-1/2}$$
$$\times \left(\frac{M_{\mathrm{cl}}}{\mathrm{M_\odot}} \right)^{1/2} \left(\frac{R_{\mathrm{ph}}}{1\,\mathrm{pc}} \right) \left(\frac{c_{\mathrm{s}}}{10.9\,\mathrm{km\,s^{-1}}} \right)^{-1}, \quad (4)$$

where n_{m} is the mean density the local ISM would have if it were homogenized. The quite smooth appearance of the bow shock (whose transverse dimension is ≈ 1 pc) implies that the local ISM is homogeneous on a scale of ~ 1 pc, so that our assumption would be correct if the mass of individual clumps is $\leqslant 0.01$ M$_\odot$ (we assumed here that $R_{\mathrm{ph}} = 1$ pc and $n_{\mathrm{m}} \approx n = 3.6\,\mathrm{cm}^{-3}$). It is difficult to make more quantitative arguments analytically, because this is a very non-linear process. We are currently using 3D radiation-magnetohydrodynamics simulations to investigate the effects of a clumpy ISM in more detail (Mackey et al., in preparation).

The current sample of Galactic candidate weak-wind stars (Martins et al. 2005, 2012; Marcolino et al. 2009) contains 22 stars (including ζ Oph). We searched for bow shocks around all these stars using the Mid-Infrared All Sky Survey carried out with the *Wide-field Infrared Survey Explorer* (*WISE*; Wright et al. 2010). This survey provides images in four wavebands centred at 3.4, 4.6, 12 and 22 μm, of which the 22 μm band is most suitable for detection of bow shocks (e.g. Gvaramadze et al. 2011; Peri et al. 2012). Besides ζ Oph, the bow shocks were detected around four stars: HD 34078, HD 48099, HD 48279, and HD 216898. The first two stars are well-known runaways (see figs. 2 and 3 in Peri et al. 2012 for the *WISE* images of their bow shocks), while the runaway status of HD 48279 (suggested by its space velocity of ≈ 30 km s^{-1} and the presence of a bow shock) was recently established by Gvaramadze et al. (2012)[1]. The bow shock around HD 216898 is detected for the first time.

Unfortunately, none of the four stars are associated with

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[1] It is believed that HD 48279 is a member of the Mon OB2 association, while the orientation of the bow shock and the vector of the stellar peculiar transverse velocity imply that the star was *injected* into the association (cf. Gvaramadze & Bomans 2008).

well-defined H II regions. There are, however, several alternative possibilities to estimate the local ISM density. For example, the pre-shock density could be derived through modelling (optical) spectra of the shocks (e.g. Dopita 1977) or from their emission measures, either in Hα or in the infrared (e.g., Bally et al. 2006; Kobulnicky et al. 2010). The latter possibility is especially attractive because bow shocks are detectable mostly in the infrared. Hydrodynamic modelling of bow shocks can also constrain the ISM density by comparing observed instabilities, bow shock mass, and emissivity to simulations (e.g. Mohamed, Mackey & Langer 2012). Further work in this direction is highly desirable in order to constrain $\dot{M}$ of a larger sample of 'weak-wind' stars.

The paucity of bow-shock-producing 'weak-wind' stars with well-defined H II regions can be compensated by detection of new examples of late O/early B type stars possessing these structures. Indeed, inspection of the SHASSA survey revealed several circular H II regions with central bow-shock-producing OB stars (Gvaramadze et al., in preparation), some of which (e.g. δ Sco, τ Sco) might belong to the group of the 'weak-wind' stars. Determination of $\dot{M}$ for these stars using different atmosphere models and their comparison with $\dot{M}_{\mathrm{obs}}$ (and $\dot{M}$ based on the work of Lucy 2010) is highly desirable as well.

To conclude, detection of bow shocks (and well-defined H II regions) around field late-type O dwarfs provides unique possibilities for resolving the weak-wind problem, which in turn would have profound consequences for better understanding the mass-loss mechanism of massive stars, their impact on the ambient ISM, and their evolution in general.

5   ACKNOWLEDGEMENTS

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